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5 Method of producing a flat zirconium alloy product,
 flat product thus obtained and a nuclear plant reactor
 grid which is made from said flat product

The invention relates to the field of flat products (plate and sheet) made of a zirconium alloy, these being used in particular for manufacturing components 10 of a light-water nuclear power reactor.

In light-water nuclear reactors, the spacer grids made 15 of zirconium alloy that retain the rods (fuel-containing tubes) form cells into which the rods are inserted and retained by assemblies of rigid means and resilient means.

These spacer grids are subjected to irradiation-induced growth, under the effect of which the dimensions of the 20 cells are modified over the course of operation of the reactor. This modification makes the retention of the rods looser and looser, and the grids end up by no longer fulfilling their role satisfactorily.

25 It has been proposed in document EP-A-0 220 060 to produce these grids from a flat product made of a fully recrystallized zirconium alloy possessing a particular texture. This texture is such that the Kearns factors measured along the transverse direction and the 30 longitudinal direction of the cell, when the grid is in place, are combined so that the irradiation of the grid during operation of the reactor causes a contraction of the cell and not an increase in its cross section. Thus, the clamping force exerted by the grid on the 35 rods tends to increase instead of decrease.

It should be noted that document EP-A-0 220 060 does not propose a process for actually obtaining the
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desired texture. Processes for obtaining this texture are known, but they cannot be used because of major problems in the corrosion behavior of the reactor.

5 The object of the invention is to propose a process for producing a flat product, whether plate or sheet, made of a zirconium alloy comprising, especially as addition element, niobium but not 100% recrystallized, which is intended especially for the manufacture of reactor
10 spacer grids of light-water nuclear power plants and which solves the problems associated with irradiation-induced growth of the metal, while still preserving sufficient corrosion resistance properties.

15 For this purpose, the subject of the invention is a process for producing a flat product made of a zirconium alloy having a Kearns factor FT of between 0.30 and 0.70, characterized in that:

20 - an ingot of zirconium alloy with the following composition, in percentages by weight, is smelted:

Nb = 0.5 to 3.5%

Sn = 0 to 1.5%

Fe = 0 to 0.5%

Cr + V = 0 to 0.3%

25 S = 0 to 100 ppm

O = 0 to 2000 ppm

Si = 0 to 150 ppm,

the balance being zirconium and impurities resulting from the smelting;

30 - said ingot is formed;

 - said formed ingot undergoes one or more hot-rolling passes in order to obtain a flat product, the final of said hot-rolling passes being carried out between $(810 - 20Nb\%)^{\circ}\text{C}$ and 1100°C and not being followed by any quenching operation from the $\alpha + \beta$ or β phase;

 - optionally, said flat product undergoes an annealing operation at a temperature not exceeding

800°C; and

- the flat product undergoes one or more cold-rolling/annealing cycles, said annealing operations not taking place above 800°C.

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In one exemplary embodiment, the Nb content of the alloy is from 0.5 to 1.5%.

10 Said final hot-rolling pass is preferably carried out at a temperature within $\pm 130^{\circ}\text{C}$ of the temperature at which the alloy undergoes the $\alpha + \beta \rightarrow \beta$ transition.

The final of said hot-rolling passes is preferably carried out between 820 - 20Nb% and 1100°C.

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Said final hot-rolling pass is preferably carried out between 900 and 1030°C.

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The invention also relates to a flat product made of a zirconium alloy having a Kearns factor FT of between 0.30 and 0.70, characterized in that it is obtained by the above process.

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Finally, the invention relates to a spacer grid for retaining the fuel rods in a light-water nuclear power plant reactor, characterized in that it is obtained by the forming of a flat product of the above type.

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As will have been understood, the invention consists in producing a flat product, which may be termed a plate or sheet product depending on its final thickness, exhibiting excellent dimensional stability under irradiation in the transverse direction (with respect to the rolling direction). This dimensional stability results from the formation, after production of the flat product, of a texture such that the Kearns factor FT in the transverse direction is equal to 0.30 or higher, and in practice between 0.30 and 0.70, as

opposed to less than 0.25 in the current standard processes and 0.4 to 0.5 in the process of EP-A-0 220 060 which, moreover, requires a fully recrystallized state of the flat product, which is
5 unnecessary in the case of the invention. In this way, if the plate is cut along a judiciously chosen direction in order to constitute, after forming, the reactor grid according to the invention, what is obtained is a grid exhibiting excellent dimensional
10 stability under irradiation in the cross section of the rod retention cells. Thus, the problems associated with excessive relaxation in the retention of the cells and, on the contrary, problems associated with eventual
15 excessive clamping of the rods in the cells are avoided.

This result is obtained by applying, to a Zr-Nb alloy (which may also contain one or more of the elements Sn, Fe, Cr, V, S, O and Si in significant amounts), heat
20 and thermomechanical treatments that will be described later.

It will be recalled that the irradiation-induced growth of the grids is determined by three parameters:

- 25 - the texture of the plate or sheet, which may be varied in order to obtain a Kearns factor going in the sense of expansion or contraction along a preferred axis (free growth); a Kearns factor of less than 0.33 in a given direction corresponds to free growth that gives rise to an expansion in this same direction and a Kearns factor of greater than 0.33 corresponds to free growth that gives rise to a contraction;
- 30 - corrosion/oxidation which will always go in the sense of expansion; and
- 35 - hydriding, which will also go in the sense of expansion.

The heat and thermomechanical treatments according to

- the invention, in combination with the composition of the alloy to which they are applied, make it possible to modify the Kearns factor FT in the transverse direction so that, taking into account the morphology 5 and the future operating conditions of the grid (for example the temperature and linear power of the reactor of which the grid forms part), little or no irradiation-induced growth is observed.
- 10 In situations in which the corrosion/oxidation and/or hydriding are slight, it will be beneficial to obtain an FT close to 0.33.
- 15 In situations in which the corrosion/oxidation and hydriding are more important, it will be beneficial to obtain a higher FT (up to 0.70) so that the irradiation-induced growth resulting from these phenomena are compensated for by a free-growth contraction resulting from the texture obtained.
- 20 The invention will be more clearly understood on reading the description that follows, given with reference to the following appended figures:
- 25 - figure 1 shows by way of reference pole figures of a specimen of a flat product made of a Zr-Nb alloy containing about 1% Nb and having undergone a final hot-rolling pass at 780°C; and
- 30 - figure 2 shows pole figures of a specimen of a flat product made of a Zr-Nb alloy containing about 1% Nb and having undergone a final hot-rolling pass at 900°C according to the invention.

The zirconium alloys to which the invention applies contain (the percentages are percentages by weight):

- 35 - 0.5 to 3.5% and particularly 0.5 to 1.5% Nb;
- preferably up to 1.5% Sn;
- preferably up to 0.5% Fe;
- preferably Cr and/or V, with Cr + V ≤ 0.3%;

- optionally sulfur, up to 100 ppm;
- optionally oxygen, up to 2000 ppm;
- optionally silicon, up to 150 ppm; and
- the inevitable impurities resulting from the smelting.

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According to the invention, after smelting and forming of an ingot having the aforementioned composition, one or more hot-rolling passes are carried out. This hot 10 rolling (the final pass thereof if there are several passes) must therefore take place while the zirconium alloy is in one of the $\alpha + \beta$ or β domains and, more precisely according to the invention, between a minimum temperature, which depends on the Nb content of the 15 alloy, and 1100°C. The minimum temperature (in °C) for this final hot-rolling pass is equal to 810 - 20Nb%. For an alloy containing 0.95% Nb, it is therefore 791°C. For an alloy containing 2.5% Nb, it is therefore 760°C. In practice, it is preferable to aim for a 20 minimum hot-rolling temperature of 820 - 20Nb% (and therefore 10°C higher than the theoretical minimum temperature defined above) for the purpose of providing a good operating margin. In particular, this thus ensures that the entire product to be rolled will be 25 always at a suitable temperature during the rolling. Preferably, this temperature of the final hot-rolling pass lies within $\pm 130^\circ\text{C}$ of the $\alpha + \beta \rightarrow \beta$ transition. The optimum temperature range is very often 900 to 30 1030°C. The reduction ratio for this final hot-rolling pass is typically between 50 and 95%.

It is imperative that this final hot-rolling pass in the $\alpha + \beta$ or β domain is not followed by any quenching operation starting from this same domain. This is 35 because β -Zr would then form when hot, which would lose the texture during the quench. This would therefore result in products having properties not according to the invention.

After this hot rolling and an optional anneal, the flat product obtained undergoes the usual cold-rolling and annealing operations, the annealing operations not 5 taking place above 800°C.

It is not absolutely essential for the flat product obtained at the end of the treatment to be in the fully recrystallized state. The 0.30 to 0.70 FT condition, 10 which guarantees low irradiation-induced growth in the transverse direction, may be satisfied even with a flat product in the relaxed or partially recrystallized state provided that the conditions of the invention are respected.

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To exemplify this, a series of trials was carried out on an ingot of a zirconium alloy having the composition (in percentages by weight) :

Nb = 0.95%	O = 1350 ppm	Fe = 0.037%
Cr = 40 ppm	S = 11-21 ppm	C = 22 ppm
N = 22 ppm	Al = 12 ppm.	

Seven types of thermomechanical treatment were carried out on this 660 mm diameter ingot: four control trials 25 (E1 to E4) and three trials according to the invention (E5 to E7), as indicated in Table 1.

Two other trials according to the invention (E8 and E9) were carried out on a 660 mm diameter ingot of the 30 following composition:

Nb = 2.50%
Fe = 0.05%
O = 1300 ppm
Si = 50 ppm.

35

Table 1 describes these various treatments.

Table 1

	E1 Control	E2 Control	E3 Control	E4 Control	E5 Invention	E6 Invention	E7 Invention	E8 Invention	E9 Invention
Forging of the ingot			900°C ($\alpha + \beta$), 200 mm thickness			900°C (β), 200 mm thickness	900°C (β), 200 mm thickness	1050°C (β), 200 mm thickness	
Forging of the slab			900°C ($\alpha + \beta$), 100 mm thickness			900°C (β), 100 mm thickness	900°C (β), 100 mm thickness	780°C ($\alpha+\beta$), 100 mm thickness	
Hot rolling			945°C ($\alpha + \beta$), 30 mm thickness			945°C (β), 30 mm thickness	945°C (β), 30 mm thickness	945°C (β), 20 mm thickness	
Intermediate quench β	Yes				No			Yes	
Hot rolling	780°C, 4.7 mm thickness	780°C, 4.7 mm thickness	700°C, 4.7 mm thickness	900°C, 4.7 mm thickness	900°C, 4.7 mm thickness	960°C, 4.7 mm thickness	945°C, 4.7 mm thickness	780°C, 6 mm thickness	
Continuous annealing	No. of cold-rolling/annealing cycles	0.425 mm thickness	0.6 mm thickness	0.425 mm thickness	700°C	2.0 mm thickness	0.5 mm thickness		

The textures of the flat products obtained from these trials were determined. The Kearns factors FN, FT and FL obtained are given in Table 2.

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Table 2

	Thickness (mm)	FN	FT	FL
Trial 1 (Control)	0.425	0.687	0.230	0.082
Trial 2 (Control)	0.6	0.709	0.208	0.083
Trial 3 (Control)	0.6	0.649	0.270	0.082
Trial 4 (Control)	0.6	0.649	0.269	0.084
Trial 5 (Invention)	0.6	0.627	0.300	0.073
Trial 6 (Invention)	0.425	0.622	0.306	0.072
Trial 7 (Invention)	0.425	0.594	0.339	0.068
Trial 8 (Invention)	2.0	0.308	0.645	0.047
Trial 9 (Invention)	0.5	0.576	0.375	0.050

In the control trials, an increase in FN and a decrease in FT are obtained as usual when the thickness of the
10 flat product decreases.

The specimens obtained by the process according to the invention have a Kearns factor FT that is significantly higher than the control specimens. If FT lies around
15 the 0.33 value (hence the lower limit of 0.30 in the case of FT for the plate products according to the invention) and if a grid is manufactured from a portion of the flat product that has been cut along a suitable orientation, it is possible to ensure that, during its
20 use, this grid will exhibit only small variations in the cross section of its cells in the absence of significant corrosion/oxidation and hydriding. If FT is significantly greater than 0.33, the tendency to

undergo irradiation-induced contraction that results therefrom makes it possible to compensate for the irradiation-induced growth resulting from the corrosion/oxidation and hydriding of the grid during
5 its use under planned conditions. Thus, both the problems that will be associated with excessive growth of this cross section under irradiation (relaxation of the clamping of the rods, weakening their retention) and the problems that will be associated with excessive
10 reduction in this cross section under irradiation (excessively large clamping force on the rods, preventing them from being inserted and extracted) will be avoided.

15 Examination of the pole figures of a specimen example obtained by the process according to the invention corresponding to trial E5 (figure 2), for which the Nb content is around 1% and the final hot-rolling pass took place at 900°C, shows that the textures are
20 clearly more transverse (high FT and low FN) than those of a control specimen of the same composition and final thickness corresponding to trial E2 (figure 1), for which the final hot-rolling pass was carried out only at 780°C.
25 It is also observed that the transverse character of the texture increases with the hot-rolling temperature, which is therefore one of the parameters, together with the composition of the alloy, which may be varied in
30 order to obtain an FT of the desired value.

For a given hot-rolling temperature (for example 960°C), this transverse character of the texture is even more accentuated when the $\alpha + \beta \rightarrow \beta$ transition
35 temperature is lowered, for example for higher Nb contents, which may have the effect that the final hot-rolling pass takes place in the pure β domain. This is the case for trial 8 described above, and to a

lesser extent for trial 9 for which the final hot-rolling pass was carried out under less severe reduction conditions and at a temperature of 780°C, and therefore in the $\alpha+\beta$ domain of the alloy.

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From the standpoint of the structure of the specimens, no clear difference may be seen between the control products and the products according to the invention after hot rolling, for comparable compositions and 10 final thicknesses.

Nor, from the standpoint of the compositions of the β -Zr and β -Nb phases and of the $Zr(Nb,Fe)_2$ precipitates, is any appreciable difference observed between the 15 control trials and the trials according to the invention by comparable alloy composition.

Nor is the corrosion resistance significantly affected by the use of the process according to the invention.

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Spacer grids for retaining the rods of nuclear power plant reactors were manufactured from the flat products according to the invention by standard forming processes.

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